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3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	University of Strathclyde 16 Richmond Street GLASGOW G1 1XQ
Patents ADP number *(if you know it)*	7984960001
If the applicant is a corporate body, give the country/state of its incorporation	UK
4. Title of the invention	Improved Vertical External Cavity Surface Emitting Laser
5. Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Kennedys Patent Agency Limited Floor 5, Queens House 29 St Vincent Place Glasgow G1 2DT
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KENNEDYS 04 December 2003

12. Name and daytime telephone number of person to contact in the United Kingdom

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Improved Vertical External Cavity Surface Emitting Laser

The present invention relates to an improved Vertical External Cavity Surface Emitting Laser (VECSEL) and in particular to a VECSEL that exhibits improved wavelength tuning characteristics.

Diode-pumped VECSELs are an attractive format of semiconductor laser known to those skilled in the art for scientific, instrumentation and non-linear optics applications. The design and fabrication of a VECSEL laser with Circular TEM_{00} output beams has been described by Kusnetsov et al (IEEE Journal of selected Topics in Quantum Electronics Vol. 5, Page 561 – 573 (1999) "*Design and Characteristics of High-Power (>0.5W CW) Diode-Pumped Vertical-External-Cavity Surface- Emitting Semiconductor Lasers with Circular TEM_{00} Beams*").

The optical gain medium within a VECSEL is provided by the recombination of electrical carriers within very thin layers of a semiconductor material. These layers are generally termed quantum-well (QW) layers or active

layers exhibiting a typical thickness of around 150 Å or less.

Application of intracavity spectral and temporal control techniques such as picosecond and subpicosecond mode-locking, single-frequency operation and intracavity second-harmonic generation have also been demonstrated see:

- Garnache et al. Appl. Phys. Lett. Vol 80 Page 3892-3894 (2002) "*Sub 500-fs Soliton-Like Pulse in a Passively Mode-Locked Broadband Surface-Emitting Laser with 100mW Average Power*";
- Holm et al. IEEE Photon. Technol. Lett. Vol 11 Page 1551-1553 (1999) "*Actively stabilised Single-Frequency Vertical-Cavity AlGaAs Laser*"; and
- Schiehlen et al. IEEE Photon. Technol. Lett. Vol 14 Page 777-779 (2002) "*Diode-Pumped Semiconductor Disk Laser With Intracavity Frequency Doubling using Lithium Triborate (LBO)*", respectively.

A significant limiting factor in all of the aforementioned systems is that their output power is greatly limited by the thermal response of the gain structure. Typically, without employing thermoelectric cooler (TEC) mounting techniques or cooling strategically deployed heat sinks with chilled water, both of which are well known to those skilled in the art, the output powers at room temperatures are limited to a few 10's of mW. The employment of these cooling methods act to improve the output powers but are generally very inefficient due to the fact that the heat must be removed from the gain medium via the substrate of the structure.

The prior art teaches of several methods for improving the efficiency of VECSEL cooling systems. The first involves growing the gain structure in reverse order, mounting on a heatsink and etching away the substrate. However, the resultant scattering due to poor surface quality remains a significant problematic feature within low gain lasers that usually tolerate only very little losses (~2%).

Alford et al. described an alternative method for removing heat from the gain region that involves no post-growth alterations to the structure (see J. Opt. Soc. Am. B Vol. 19, Page 663 (2002) "*High Power and Good Beam Quality at 980nm from a Vertical External-Cavity Surface-Emitting Laser*"). In particular this document teaches of an InGaAs-based VECSEL that employs, in conjunction with a thermoelectric cooler, a sapphire heatspreader capillary bonded in optical contact with the epi-side (or active surface) of the gain structure. More recently, Hastie et al. have described a VECSEL that employs an intracavity Silicon Carbide (SiC) heatspreader that is optically contacted to the active surface of the gain medium (see IEEE Photon. Technol. Lett. Vol 15 Page 894-896 (2003) "*0.5 W Single Transverse-Mode Operation of an 850nm Diode Pumped Surface-Emitting Semiconductor Laser*"). Generally, Silicon Carbide has been shown to exhibit superior heat spreading characteristics than heatspreaders comprising Sapphire.

In order to produce single frequency operation it is known to those skilled in the art to incorporate intracavity polarisation selecting elements such as birefringent filters, orientated at Brewster's angle, and

an etalon within the laser cavity. Wavelength scanning can then be achieved via a number of known techniques e.g. the incorporation of stabilisation to a side of a transmission peak of an external reference cavity. Such techniques are currently employed to produce tuneable Ti:Sapphire and Dye lasers that find particular application in the field of high resolution spectroscopy.

It is known that the gain medium of a VECSELs possesses a relatively high gain bandwidth that provides the potential for a VECSEL to be tuned approximately 20 nm either side of the engineered wavelength. However, in practice it has been found that the above laser frequency stabilisation and wavelength scanning techniques do not lend themselves to be readily incorporated within the described VECSELs. This is principally due to the fact that there is significant modulation of the output power of the VECSEL as the laser's operating wavelength is scanned (between 10 – 30%) due to the heatspreader acting as an additional intracavity etalon. Furthermore, both Sapphire and Silicon Carbide heat spreading elements are found to interfere with the polarisation selection properties of any intracavity birefringent filter thus reducing the frequency stability and tuneability of the cavity.

It is an object of aspects of the present invention to provide a Vertical External Cavity Surface Emitting Laser (VECSEL) that overcomes one or more of the limiting features on frequency stability and wavelength tuning associated with the VECSELs described in the prior art.

The term "active surface" used throughout the specification in relation to one or more of the intracavity elements of the VECSEL refers to that surface on which the optical pumping field is initially incident.

According to a first aspect of the present invention there is provided a Vertical External Cavity Surface Emitting Laser comprising a wafer structure and a heatspreader located at an active surface of the wafer structure wherein the heatspreader comprises a non-birefringent material.

Preferably the heatspreader comprises an anti-reflection coating located on an active surface of the heatspreader.

According to a second aspect of the present invention there is provided a Vertical External Cavity Surface Emitting Laser comprising a wafer structure and a heatspreader located at an active surface of the wafer structure wherein the heatspreader comprises an anti-reflection coating located on an active surface of the heatspreader.

Preferably the heatspreader comprises a non-birefringent material.

According to a third aspect of the present invention there is provided a Vertical External Cavity Surface Emitting Laser comprising a wafer structure and a heatspreader located at an active surface of the wafer structure wherein the heatspreader comprises a non-birefringent material and an anti-reflection coating located on an active surface of the heatspreader.

Preferably the anti-reflection coating is optimised for efficient operation with a refractive index of the non-birefringent material.

Preferably the active surface of the heatspreader comprise a wedge.

Most preferably the heatspreader comprises a single diamond crystal.

Preferably the laser further comprises an intracavity polarisation selecting element that provides a first means for selecting the operating wavelength of the laser.

Preferably the intracavity polarisation selecting element comprises a birefringent filter orientated at Brewster's angle.

Preferably the laser further comprises an intracavity etalon that provides a second means for selecting the operating wavelength of the laser.

Optionally the laser comprises a three mirror folded cavity arrangement.

Preferably the laser further comprises an external reference cavity that allows for the frequency stabilisation of the laser output to a side of a transmission peak of the external cavity.

Preferably the laser further comprises a cavity mirror mounted on a first piezoelectric crystal and an output coupler mounted on a second piezoelectric crystal wherein the combined movement of the cavity mirror and the output coupler provides a first means for tuning the output wavelength of the laser.

Alternatively, the laser further comprises a pair of Brewster plates and a cavity mirror mounted on a piezoelectric crystal wherein the combined movement of the Brewster plates and the cavity mirror provide a second means for tuning the output wavelength of the laser.

According to a fourth aspect of the present invention there is provided a scanning Vertical External Cavity Surface Emitting Laser suitable for use in high resolution spectroscopy experiments comprising apparatus for selecting and stabilising the operating frequency of the laser, apparatus for scanning the operating frequency of the laser, a wafer structure and a heatspreader located at an active surface of the wafer structure wherein the heatspreader comprises a non-birefringent material and an anti-reflection coating located on an active surface of the heatspreader.

Preferably the apparatus for selecting and stabilising the operating frequency of the laser comprises an intracavity polarisation selecting element, an intracavity etalon and an external reference cavity.

Preferably the apparatus for scanning the operating frequency of the laser comprises a cavity mirror mounted

on a first piezoelectric crystal and an output coupler mounted on a second piezoelectric crystal wherein the combined movement of the cavity mirror and the output coupler provides a first means for tuning the output wavelength of the laser.

Alternatively, the apparatus for scanning the operating frequency of the laser comprises a pair of Brewster plates and a cavity mirror mounted on a piezoelectric crystal wherein the combined movement of the Brewster plates and the cavity mirror provides a second means for tuning the output wavelength of the laser.

Preferably the anti-reflection coating is optimised for efficient operation with a refractive index of the non-birefringent material.

Preferably the active surface of the heatspreader comprise a wedge.

Most preferably the heatspreader comprises a single diamond crystal.

Aspects and advantages of the present invention will become apparent upon reading the following detailed description and upon reference to the following drawings in which:

Figure 1 presents a schematic representation of an improved Vertical External Cavity Surface Emitting Laser (VECSEL) that incorporates intracavity elements for single frequency selection;

Figure 2 presents:
(a) a schematic representation; and
(b) a schematic bandgap diagram,
of the gain medium of a 980 nm VECSEL of Figure 1;

Figure 3 presents further detail of the cooling apparatus and a heatspreader employed by the VECSEL of Figure 1;

Figure 4 presents an output power curve, as a function of pump power, for the VECSEL of Figure 1 designed to operate around a 980 nm central output wavelength;

Figure 5 presents a measured residual frequency noise output for the 980 nm VECSEL of Figure 1; and

Figure 6 presents a measured wavelength tuning curve for the 980 nm VECSEL of Figure 1 when coupled to a transmission peak of an external reference cavity.

Referring to Figure 1 a schematic representation of a Vertical External Cavity Surface Emitting Laser (VECSEL) 1, in accordance with an aspect of the present invention is provided. The VECSEL 1 can be seen to comprise a wafer structure 2 mounted within a cooling apparatus 3 that is located within a three mirror folded cavity arrangement.

A first mirror within the cavity arrangement comprises a Bragg reflector 4 associated with the wafer structure 2 (further details of which are outlined below). A second mirror comprises a standard curved cavity mirror 5 mounted on a first piezoelectric crystal 6 so allowing for fine adjustment of the length of the cavity. An output coupler 7, mounted on a second piezoelectric crystal 8 so allowing for coarse adjustment of the length of the cavity, is then employed as the third cavity mirror. Between the curved cavity mirror 5 and the output coupler 7 are located a birefringent filter 9 employed to provide coarse frequency selection within the cavity and a solid etalon 10 employed for fine frequency selection of the operating wavelength. The wafer structure 2 is optically pumped by initially coupling the output of a pump laser source (not shown) into an optical fibre 11. Thereafter, the coupled pump laser output is focussed via two input lens elements 12 onto the wafer structure 2.

A schematic representation of the wafer structure 2 is presented in Figure 2(a). The wafer structure 2 is grown by a metal-organic chemical vapour deposition (MOCVD) technique on a 2 inch (5.08 cm) 500 mm thick (001) GaAs substrate 13. The wafer structure 2 comprises a lower end single distributed Bragg reflector 4, a gain medium 14, a carrier confinement potential barrier 15 and an oxidation prevention layer 16.

The Bragg reflector 4 comprises thirty pairs of AlAs-GaAs quarter-wave layers that exhibit a total reflectivity greater than 99.9% centred at 980 nm while the carrier confinement potential barrier comprises a single

wavelength-thick $Al_{0.3}Ga_{0.7}As$ layer. The oxidation prevention layer comprises a thin $In_{0.48}Ga_{0.52}P$ cap.

The gain medium 14 comprises twelve 6 nm thick $In_{0.16}GaAs$ quantum wells equally spaced between half-wave $Al_{0.06}Ga_{0.8}As/GaAsP$ structures that allow the VECSEL 1 to be optically pumped at 808 nm while generating an output in the range of 970 - 995 nm. (referred to below as the 980 nm VECSEL)

A schematic representation of the lasing mechanism is presented in the bandgap diagram of Figure 2(b). The pump field 17 is absorbed in the barrier regions and carriers thereafter diffuse into the quantum wells so as to produce the required population inversion for lasing to take place.

Figure 3 presents further detail of the cooling apparatus 3 and heatspreader 18 employed in order to improve the operating characteristics of the VECSEL 1. In particular the cooling apparatus 3 comprises a standard thermoelectric cooler 19 while the heat spreader 18 comprises a single diamond crystal that comprises an external, wedged face 20. A high performance anti-reflection coating is deposited on the surface of the wedged face 20.

The single diamond crystal heatspreader 18 is bonded in optical contact with the active surface of the wafer structure 2. The wafer structure 2 and heatspreader 18 are then clamped on top of a layer of indium foil 21 onto the thermoelectric cooler 19.

Single diamond crystal is suited to be employed as the heatspreader 18 since it exhibits comparable thermal conductivity levels as Sapphire and Silicon Carbide. Thus, the described arrangement allows the heatspreader 18 to immediately spread the heat associated with the pump field 17 to the cooling apparatus 3 after it has propagated only a limited distance into the gain medium 14, so significantly increasing the efficiency of the device. In addition there are further inherent advantages of employing the single diamond crystal as the heatspreader 18 over those described in the prior art. These reside in the fact that the single diamond crystal is non-birefringent. As such the presence of the heatspreader 18 no longer interferes with polarisation selecting properties of the birefringent filter 9 and so there are no additional intracavity losses experienced on the output of the VECSEL 1 as the laser is tuned (see Figure 6 below).

The lack of birefringence within the heatspreader 18 also allows for an optimised anti-reflection coating to be applied to the wedged surface 20. It is known to those skilled in the art that in order to optimise an anti-reflection coating it is necessary that the refractive index of the medium to which the coating is to be applied is known to a high degree of accuracy. Therefore, if the heatspreader 18 were to exhibit birefringence (as is the case for Sapphire and Silicon Carbide) two effective refractive indices would be present. A direct result of this is that the effective refractive index experienced by a propagating optical field of a fixed polarisation would be critically dependent on the orientation of the heatspreader 18 within the VECSEL 1, restricting

alignment to a single orientation only. Practically this would significantly complicate the already difficult cavity alignment process.

However, this is not the case with the single diamond crystal heatspreader 18 thus permitting the incorporation of the anti-reflection coating. The anti-reflection coating acts to significantly reduces the power modulation effects, caused by the presence of the intracavity heatspreader 18, experienced when the 980 nm VECSEL is wavelength tuned (see Figure 6 below).

Figure 4 provide some typical operational characteristics of the described VECSEL 1 systems in the absence of the birefringent filter 9 and the solid etalon 10. In particular Figure 4 presents the 980 nm VESCEL output power as a function of pump power, when the heatsink temperature was maintained at 10°C. The pump power was provided by a commercially available 200 µm fibre coupled laser that generated a 25 W pump field at 808 nm. A 2% output coupler 7 was employed so producing a maximum output power of 1.75 W in a TEM_{00} mode with 6.2 W of pump power.

On introducing the birefringent filter 9, the solid etalon 10 and a 1% output coupler 7 to the cavity it is possible to stabilise the output frequency of the device to the side of a transmission peak of an external reference cavity (not shown). The operational characteristics of the 980nm VECSEL are shown in Figure 5. The VECSEL 1 can be seen to operate at a single frequency exhibiting a residual frequency

fluctuation amounting to a linewidth of around 85 kHz r.m.s.

By employing the first 6 and second piezoelectric crystals 8 the curved cavity mirror 5 and the output coupler 7, respectively, can be translated so as to allow for the tuning of the output wavelength of the VECSEL 1. A typical tuning curve for the 980nm VECSEL is presented in Figure 6. It should be noted that the modulation in the output power can be seen to have been reduced to less than 5%.

An alternative means for tuning the laser cavity comprises the introduction of a pair of Brewster plates (not shown) into the laser cavity. When the orientation of the Brewster plates are rotated in conjunction with the translational movement of the curved cavity 5 mirror mounted on the piezoelectric crystal 6 the output wavelength of the laser can be scanned, as is known to those skilled in the art.

As will be apparent to those skilled in the art alternative gain medium 14 may be incorporated within the VECSEL 1 in order to provide different operating wavelength ranges. Furthermore, the VECSEL outlined above has been described in relation to a three mirror folded cavity chosen for ease of engineering. However, it will again be readily apparent to those skilled in the art that alternative cavity arrangements may be employed without departing from the scope of the invention. For example the laser cavity may be established between the Bragg reflector 4 and a curved output coupler 7.

The VECSEL described above employs a non-birefringent heatspreader that allows the full tuning potential of the associated gain medium to be exploited. Single diamond crystal is employed as the heatspreader since it provides the required level of thermal conductivity so as to act as an efficient heatspreader. The fact that the heatspreader is non-birefringent means that there is no detrimental interaction between the heatspreader and the polarisation selecting properties of an intracavity birefringent filter employed for coarse frequency selection within the cavity. Furthermore, the fact that heatspreader is non-birefringent allows the application of an optimised anti-refection coating to a wedged surface of the heatspreader so as to significantly reduce the modulation on the output power experienced by prior art systems.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. The described embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilise the invention in various embodiments and with various modifications as are suited to the particular use contemplated. Therefore, further modifications or improvements may be incorporated without departing from the scope of the invention herein intended.

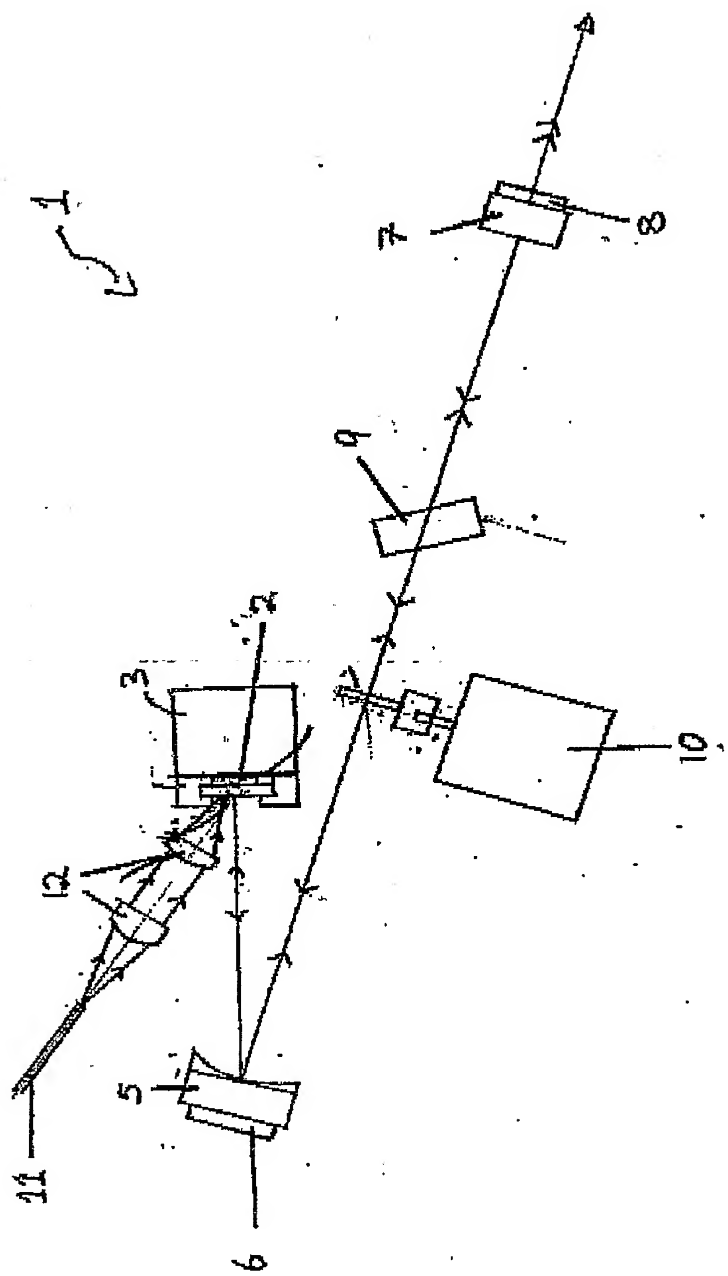
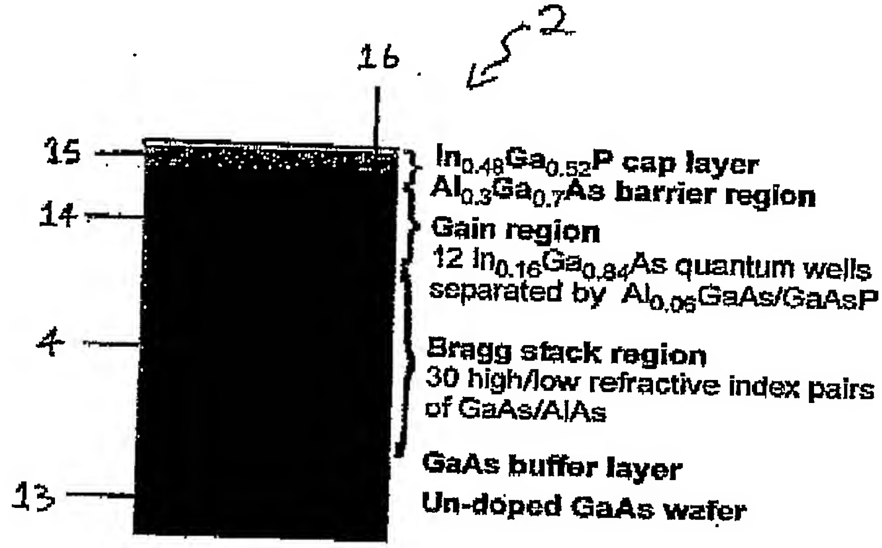
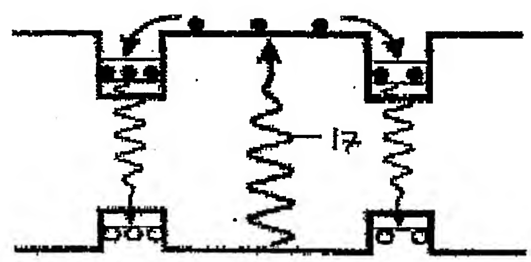


FIGURE 1


2
16
15
14
4
13
$In_{0.48}Ga_{0.52}P$ cap layer
$Al_{0.3}Ga_{0.7}As$ barrier region
Gain region
12 $In_{0.16}Ga_{0.84}As$ quantum wells separated by $Al_{0.06}GaAs/GaAsP$
Bragg stack region
30 high/low refractive index pairs of GaAs/AlAs
GaAs buffer layer
Un-doped GaAs wafer

(a)


17

(b)

FIGURE 2

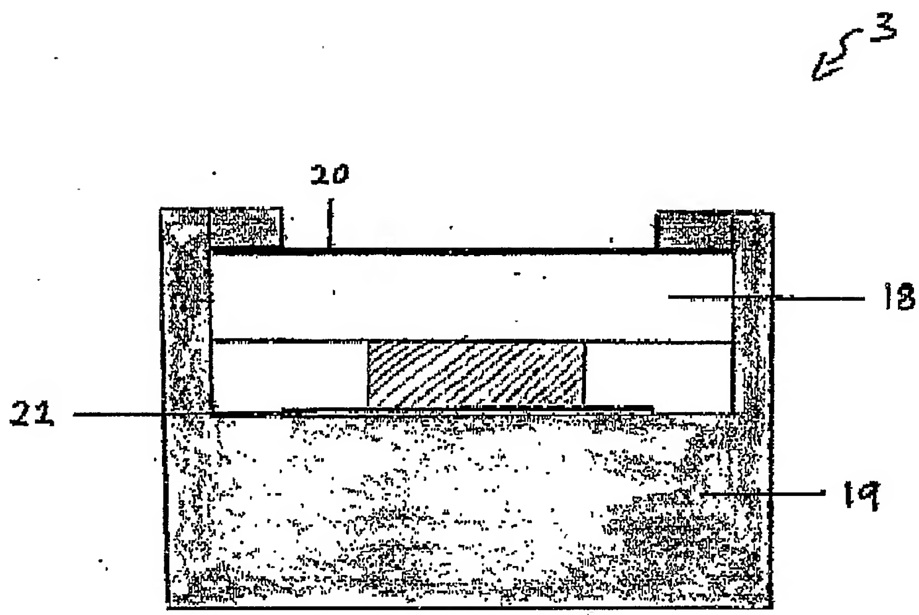


FIGURE 3

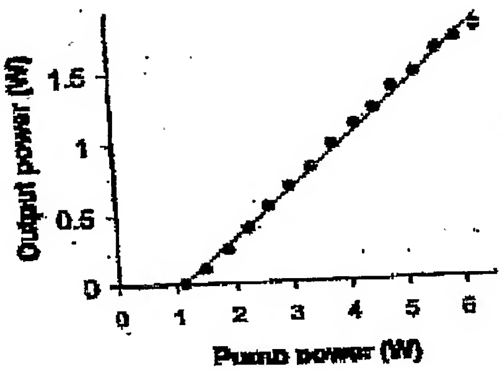


FIGURE 4

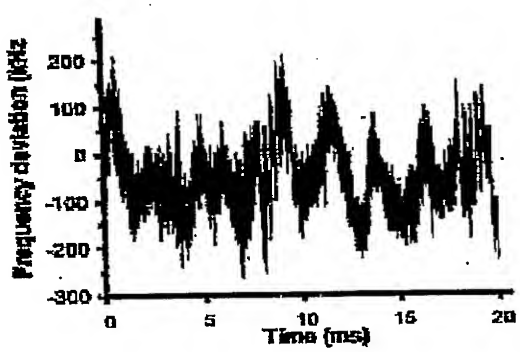
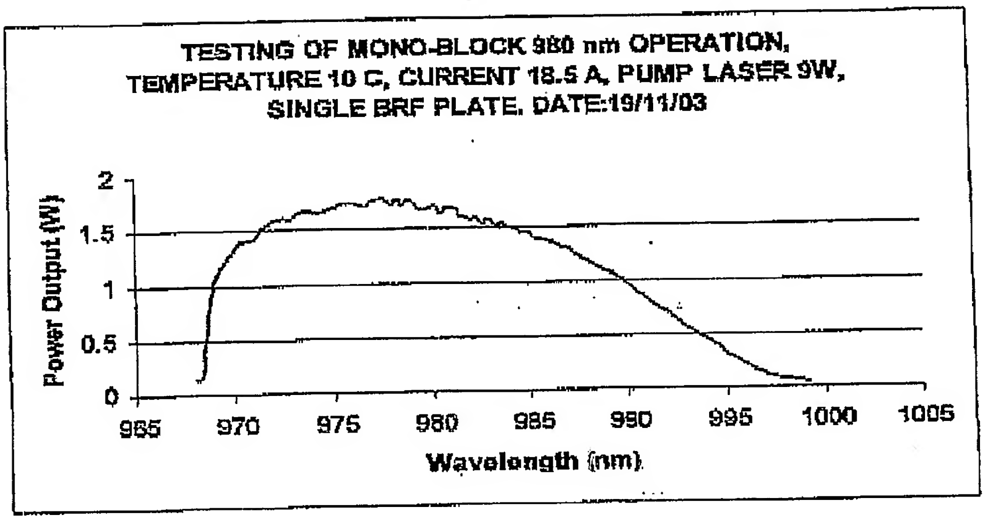


FIGURE 5



TESTING OF MONO-BLOCK 980 nm OPERATION, TEMPERATURE 10 C, CURRENT 18.5 A, PUMP LASER 9W, SINGLE BRF PLATE. DATE:19/11/03
Power Output (W)
2
1.5
1
0.5
0
965
970
975
980
985
990
995
1000
1005
Wavelength (nm)

FIGURE 6